Development and testing of large format MCT arrays for EO

Mark Herrington
10/12/2018

LEONARDO
LAND & NAVAL DEFENCE ELECTRONICS

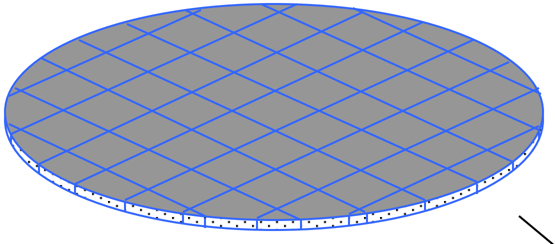
1948 · 2018

Infrared Detector Space flight Programmes

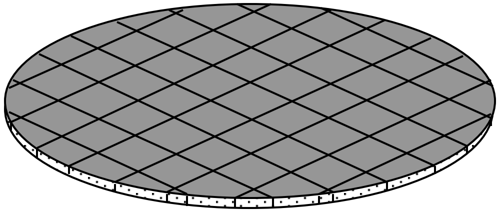
1972 Selective chopper radiometer
Nimbus 5 for NASA in collaboration with University of Oxford
1974 Horizon sensor – X4 Miranda Earth Satellite UK/USA
1975 IR spin scan radiometer
Synchronous meteorological satellite for Hughes Corporation
1977 Meteosat 1st generation
1991 ATSR (Along track scanning radiometer) – UARS for RAL
1998 PMIRR (Pressure modulated infra red radiometer)
Mars Mariner for University of Oxford
2000 STRV2 – 2 colour PV array for DERA/BMDO
2001 BIRD (bispectral integrated detector cooler assembly) – DLR
2002 MIPAS (Michelson interferometer for passive atmospheric sounding)
Envisat for ESA
2003 Raytheon Mini TES on NASA's Mars Spirit and Opportunity Rovers
2004 Meteosat 2nd generation (MSG)
2016 OSIRIS-REx thermal emission spectrometer (OTES)
NASA asteroid sample return mission
2018 GOSAT 2 - Greenhouse Gas Observing Satellite-2 FTIR – JAXA mission

2020 Planetary Science Mission – Study of climate and atmosphere
2021 NASA LUCY mission to Jupiter's Trojan asteroids
2021 IASI NG to be launched on MetOp SG A
2022 NASA PACE OCI SWIR detectors

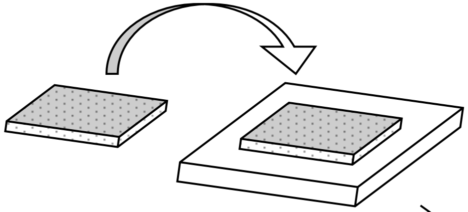
MCT Array Manufacturing



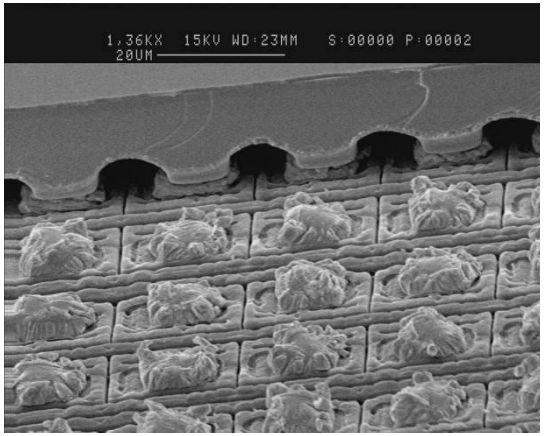
Silicon ROIC wafer with indium bumps



Crystal of HgCdTe (MCT) grown on GaAs wafer, indium applied



Flip-chip bonder for **Indium bump hybridisation**



ROICs for Space & Astronomy Applications

ME910 Saphira	Shortwave Avalanche PHotodiode for Infra-Red Applications
ME930 LFNIR	Large Format Near Infra-Red
ME950 SWIR	Large format Short Wave Infra-Red
ME1070	Large format Saphira

ROIC	ME910 Saphira	ME930 LFNIR	ME950 SWIR	ME1070
Array Format	320 x 256	1280 x 1032	2056 x 2048	1024 x 1024
Pixel Pitch	24µm	15µm	17µm	15µm
CMOS Technology	0.6µm	0.35µm	0.35µm	0.35µm
Pixel Design	Source Follower	Source Follower	Source Follower	Source Follower
Radiation hard cell library		√	√	√
Number of Video Outputs	4 / 8 / 16 / 32	4 / 8 / 16 / 32	16	16
Max. Frame Rate	4kHz	5Hz	40Hz	15Hz

Radiation hardened techniques for ROICs

- Radiation hardened standard cell library developed by Leonardo
  - ME950 SWIR, ME930 LFNIR and ME1070 use this library
  - Digital circuits implemented with this library are immune to latch-up up to 67MeV/mg/cm^2
- Triple majority voting circuits
- Radiation Hardened By Design of sequential circuit (e.g. D-type flip-flop)
- Radiation hardening design by critical charge analysis technique
- Analogue circuits hardening by layout techniques

LFNIR Heavy Ion Test Campaign

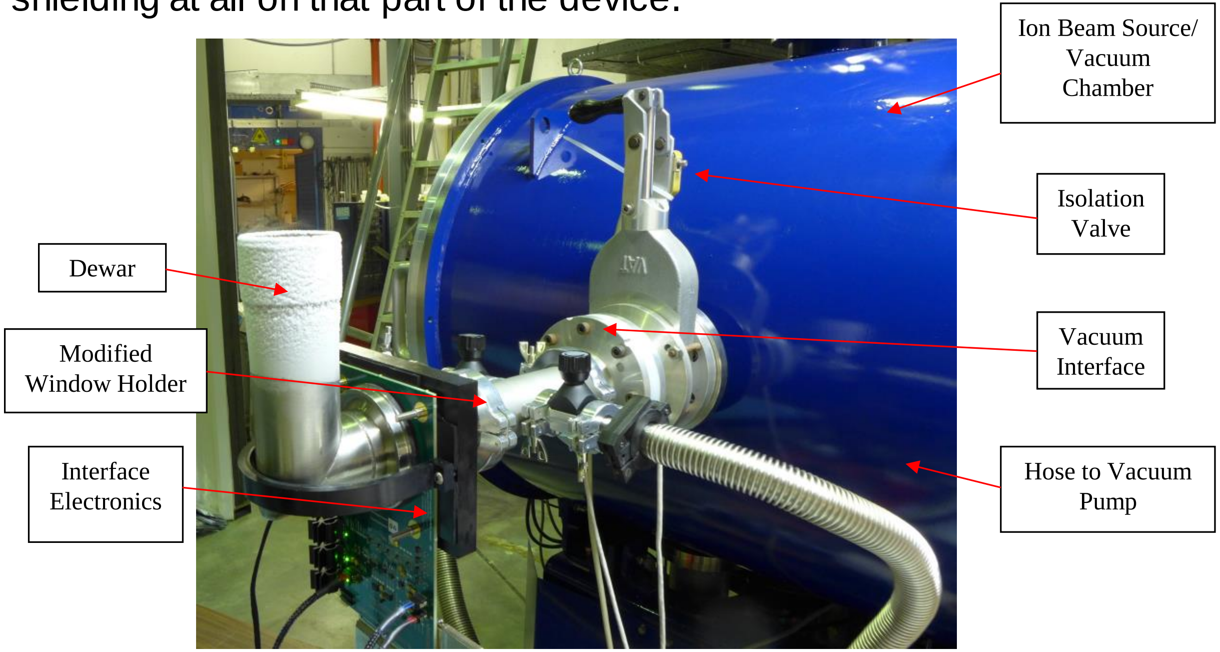
November 2014, UCL Cyclotron, Belgium

Large Format Near Infra-Red ROIC heavy ion test campaign

Testing at cryogenic (80K) and room temperature

Two types of devices tested:

- ROICs hybridised with thinned CMT to minimise the shielding of the silicon by the CMT.
- Bare silicon ROICs with a thin indium flash on half of the array to tie all of pixels on that half of the array to a fixed voltage (the indium flash is expected to offer less shielding than the thinned CMT on the hybridised samples). Pixels on the remaining half are left floating so that there is no shielding at all on that part of the device.



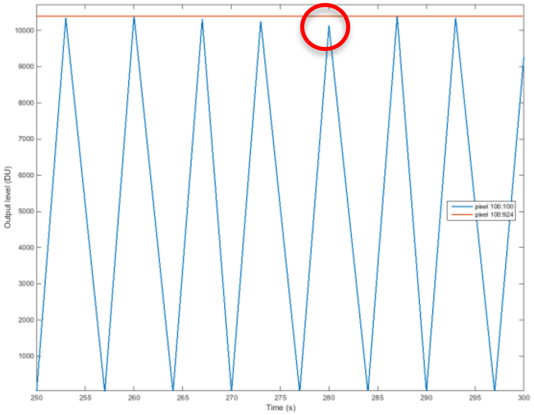
LFNIR Heavy Ion - Test Results Summary

- Devices irradiated whilst operating at cryogenic temperatures
- Devices tested shown to be immune to Single Event Latch-up up to LET of 67MeV/mg/cm^2
- 60% frame readout operability up to LET of 67MeV/mg/cm^2
- Normal functionality restored via soft reset (no need for power cycling)
- Significant step towards TRL5
- Validates Leonardo radiation hardened standard cell library and design practices
- Enables read across for ME950 ROIC (uses similar circuits and shares radiation hardened standard cell library)

LFNIR Proton irradiation - Test Results Summary

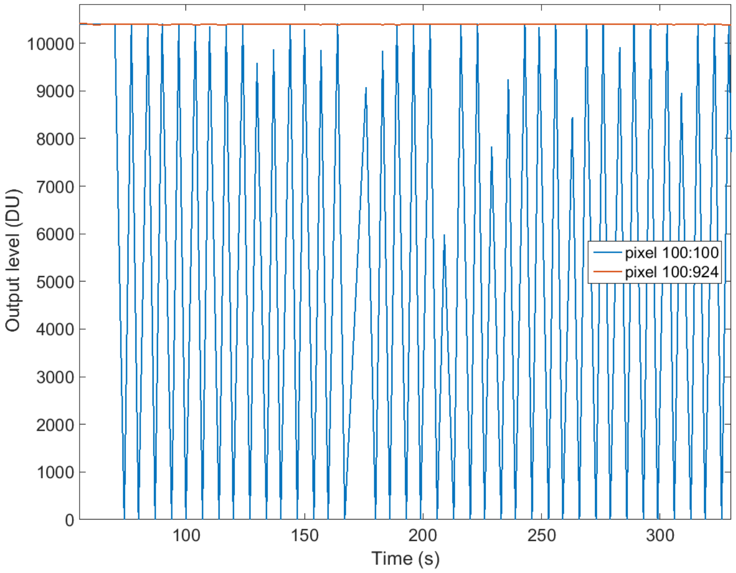
Flux (Protons cm^{-1} s^{-1})	**Approximate number of proton per pixel per frame**	**Fluence (Protons cm^{-1})**	**Cumulative Fluence**
1E6	12	6E8	6E8
5E6	60	3E9	3.6E9
1E7	120	6E9	9.6E9
2E7	240	1.2E10	2.16E10
4E7	480	2.40E10	4.56E10

- Proton bean energy fixed at 62 MeV, ~ 55MeV at the array
- No latch up or dropped frames observed at any flux
- At the highest flux an increase in the reset time is required



LFNIR Proton irradiation - Test Results Summary

Energy (MeV)	Flux (Protons $cm^{-1} s^{-1}$)
49.7	1E7
40.8	1E7
30.1	1E7
20.5	1E7
25.8	1E7
30.1	1E7

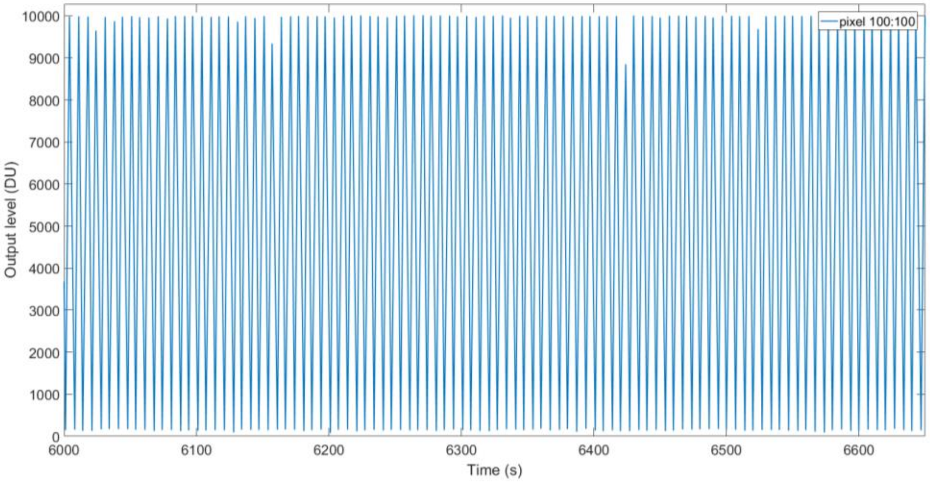


- Down to energies of 40.9 MeV device performs exactly as expected. No latch up or lost frames. Pixels return to reset level in a single reset period
- At 30.1 MeV device still operates as expected with no latch ups or missed frames
  - However pixels do not always return to the reset level in a single reset period
  - As before could be corrected by increasing the reset period
- Below 30.1 MeV no proton events detected either
  - No protons are getting through the cryostat window and cold filter
  - Or the energy is not sufficient to get over the bandgap

LFNIR Proton irradiation - Test Results Summary

Energy (MeV)	**Flux (Protons cm^{-1} s^{-1})**	**Fluence (Protons cm^{-1})**	**Cumulative fluence (Protons cm^{-1})**
62	2E7	7.2E10	7.2E10
62	2E7	7.2E10	1.4E11
62	2E7	1.36E11	2.8E11

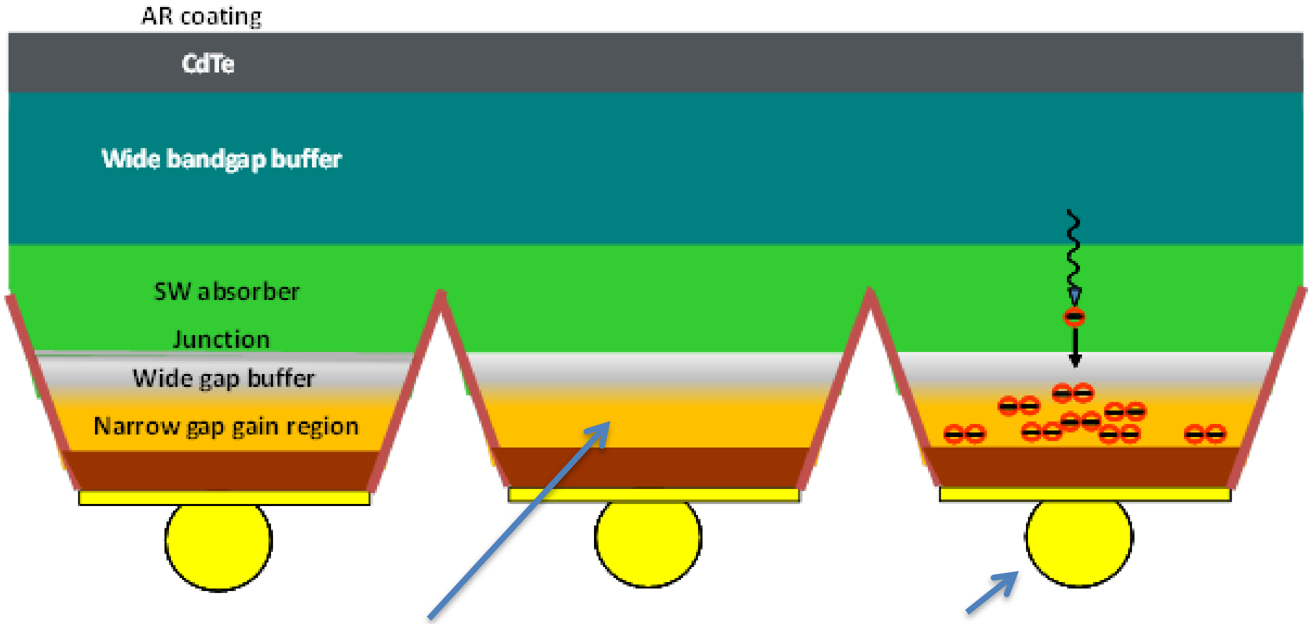
- Total log data from the third run showing that the device is still operating as expected after the total dose
- Device is still able to reset and read out on demand
- No latch ups observed and no dropped frames



LFNIR proton irradiation- Test Results Summary

- The LFNIR ROIC is immune to proton irradiation of energies up to 62 MeV at the cryostat window (~ 55 MeV at the ROIC) and fluxes of 4E7 Protons cm^{-1} s^{-1}
- After a total fluence of 2.8E11 protons cm^{-1} the device is still completely operational with no latch ups or lost frames detected.
- Individual pixel events can be recovered in all most the most extreme cases with a single reset.
  - Increasing the reset period is expected to recover even this extreme events
- Read across can be used to validate at the bid phase the use of the current radiation hard cell library for flight missions

MCT Avalanche photodiodes (APDs)



Bandgap engineering around the p-n junction switches off junction related dark current and allows up to 19V bias for avalanche gain of x450

Inter-diffused CdTe creates graded-bandgap surface to eliminate surface currents and makes arrays stable for >1 year at 70ºC

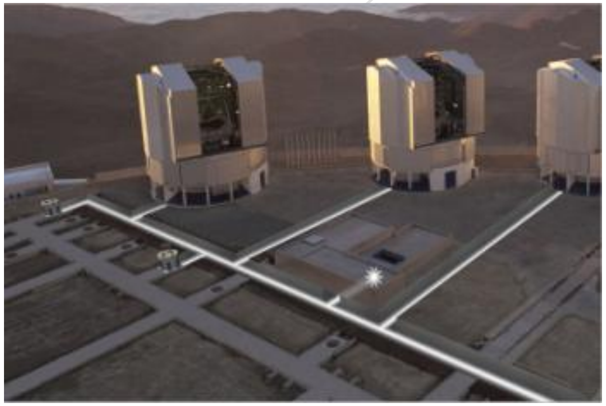
MOVPE layer control minimizes thermal diffusion current and 1/f noise

Indium bump ball

Credit ESO

VLT Interferometer and GRAVITY (virtual 130 m telescope)

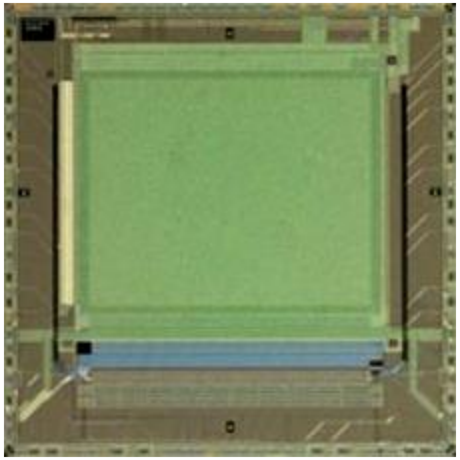
Max Planck Institute and European Southern Observatory

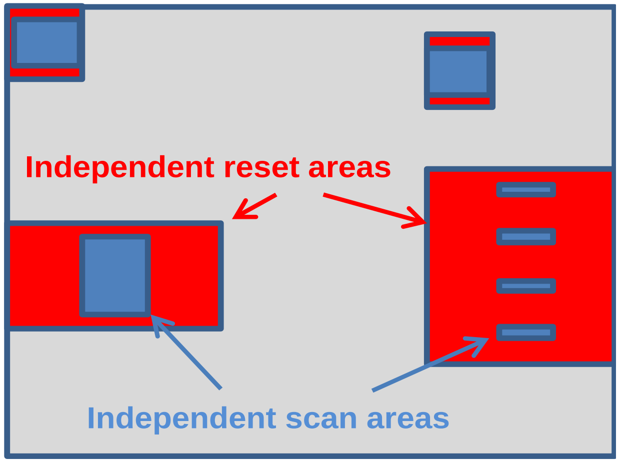


Credit ESO

SAPHIRA design and operation in GRAVITY

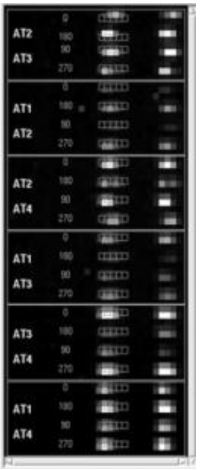
SAPHIRA 320x256/24µm

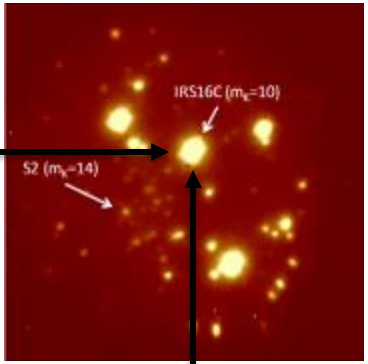


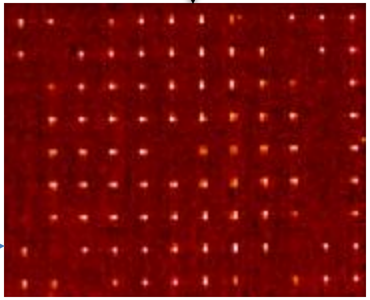


Independent reset areas

Independent scan areas







All four telescopes locked together to a few nanometres by one SAPHIRA running at 200,000 frames/sec and gain of x50.

Each telescope has one SAPHIRA observing the same star and controlling atmospheric distortion giving a similar resolution to a space-based telescope

Red shift in high gravity predicted by Einstein confirmed in July 2018

MCT APDs Ionising radiation exposure

Test summary

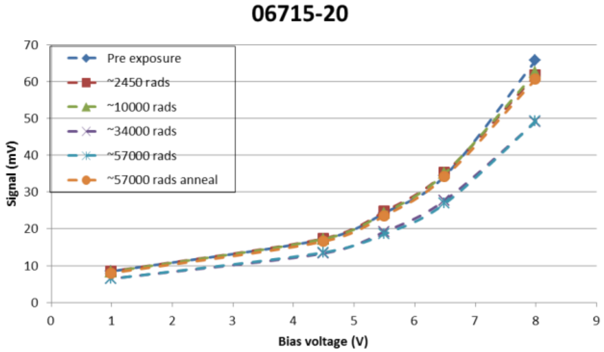
Device	06715-20			
Irradiation step No	1	2	3	4
Dose (krad)	2.5	7.5	24	23
Cumulative total dose (krad)	2.5	10	34	57
Dose rate (rads/hr)	360	360	360	360
Powered	✓	✓	Partially	✗
Device	06715-24			
Irradiation step No	1	2	3	4
Dose (krad)	1	8	7	15
Cumulative total dose (krad)	1	9	16	31
Dose rate (rads/hr)	360	360	360	360
Powered	✓	✓	✓	Partially[1]

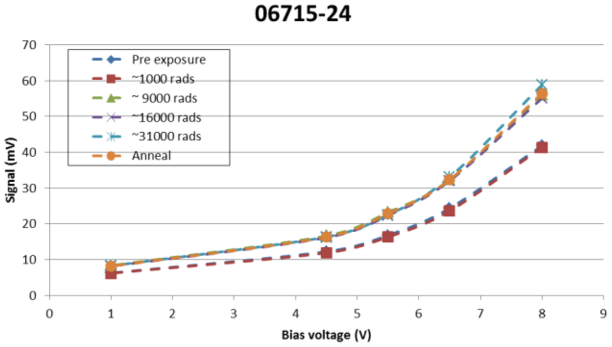
- Two devices were exposed to ionising radiation whilst powered
  - Devices were exposed with a photodiode bias of 5.5 V for device 06715-20 and 8 V for device 06715-24
  - Both devices were exposed for a TID of 28 krads whilst powered

[1] Test kit powered down after a total dose of 28 krads. The balance of the exposure between this and the end of this irradiation step was unpowered.

MCT APDs Ionising radiation exposure

Intermediate test results





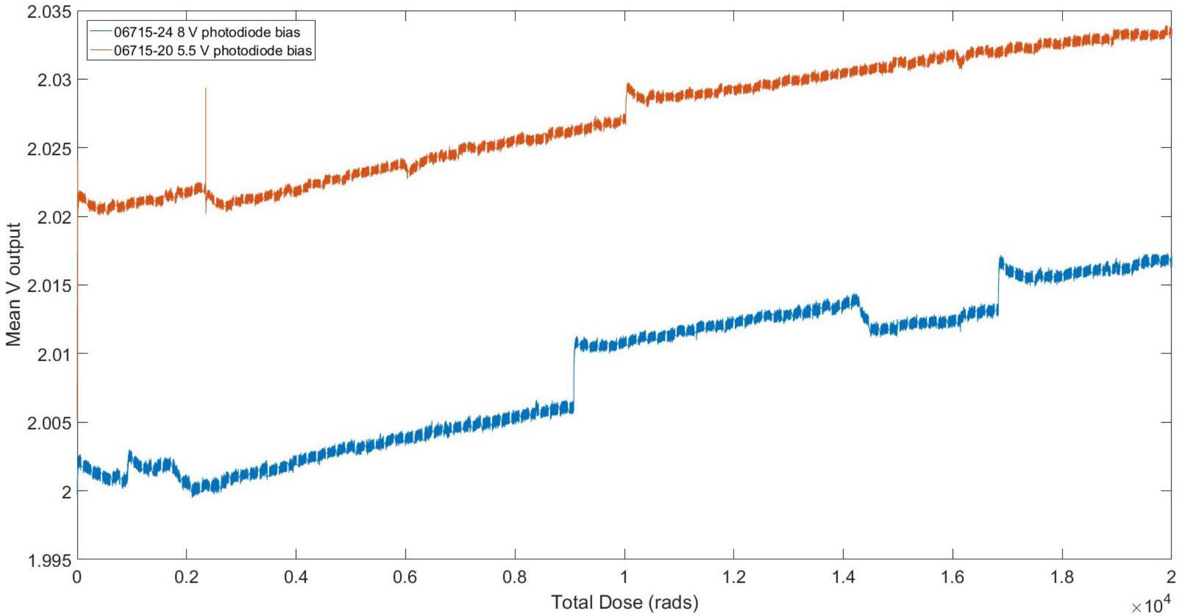
Parameter	Pre-exposure	1st intermediate test	2nd intermediate test	3rd intermediate test	Post exposure test	Room temperature Anneal/Final test
06715-20[1]						
APD gain exponent	0.401	0.367	0.378	0.377	0.392	0.380
Quantum efficiency	76.4	71.8	72.5	57.0	66.4	70.5
Excess noise factor (Max)	1.19	1.00	1.00	1.03	1.07	0.98
Read noise @unity gain (mV)	0.468	0.424	0.547	0.363	0.370	0.447
Dark Noise @ 100 K (mV)	0.827	0.623	0.676	0.590	0.561	0.734
Dark Current @100 K (electrons/pixel/second)	2.21E+05	2.22E+05	2.19E+05	2.18E+05	2.16E+05	2.17E+05
06715-24[2]						
APD gain exponent	0.364	0.371	0.354	0.361	0.384	0.363
Quantum efficiency (%)	48.5	47.9	65.1	63.9	68.2	65.5
Excess noise factor (Max)	1.10	1.07	1.11	1.07	1.00	1.12
Read noise @unity gain (mV)	0.449	0.359	0.393	0.338	0.485	0.377
Dark Noise @ 100 K (mV)	0.556	0.735	0.649	0.613	0.665	0.637
Dark Current @100 K (electrons/pixel/second)	2.20E+05	2.20E+05	2.17E+05	2.16E+05	2.16E+05	2.14E+05

- Most significant variation is seen in the in the QE results (step changes)
  - Investigation showed that this was due to the laser moving in its friction clamp and leading to a variation in the signal flux not a device variation

[1] Exposures were 2.5krads, 10krads, 34krads and 57krads. Between 34 krads and 57 krads the device was run unbiased over the weekend
[2] Exposures were 1 krad, 9krads, 16 krads and 31krads

MCT APDs Ionising radiation exposure

Voltage threshold shift



- During the exposure every 2 s 16 frames of data were captured and the mean value stored
- Increase in the mean output voltage seen with time
- This is due to a voltage threshold shift within the ROIC
- Can be adjust for by changing PRV
- Estimated that the devices could be operated up to a TID of ~200 krads without any detrimental effects

MCT APDs Ionising radiation exposure

Pre and post exposure characterisation

Parameter	Pre-exposure	Post exposure
06715-20 (TID of 57 Krads)		
Cut-off wavelength @ 100 K (µm)	2.48	2.42
Cut-off wavelength @ 140 K (µm)	2.44	2.39
APD gain exponent	0.362	0.352
Quantum efficiency (%)	77.9	70.9
Excess noise factor (Max)	1.03	0.98
Read noise @unity gain (mV)	0.334	0.315
Dark Noise @ 100 K (mV)	0.325	0.209
Dark Current @100 K (electrons/pixel/second)	6661.80	2182.08
06715-24 (TID of 31 Krads)		
Cut-off wavelength @ 100 K (µm)	2.43	2.45
Cut-off wavelength @ 140 K (µm)	2.43	2.44
APD gain exponent	0.340	0.331
Quantum efficiency (%)	56.3	64.5
Excess noise factor (Max)	1.02	1.03
Read noise @unity gain (mV)	0.332	0.301
Dark Noise @ 100 K (mV)	0.253	0.226
Dark Current @100 K (electrons/pixel/second)	2698.71	3847.53

- No evidence of any permanent degradation of either device due to the ionising radiation exposure
- Leonardo MW MCT APDs are resistant to ionising radiation of at least 28 krads powered and at least 57 krads unpowered

MCT APDs proton irradiation exposure

Test summary

Device	Exposure temperature	1st irradiation dose/cumulative dose (proton.cm-2)	2nd irradiation dose/cumulative dose (proton.cm-2)	3rd irradiation dose/cumulative dose (proton.cm-2)
06715-14	Ambient	1.48×10^{10}/ 1.48×10^{10}	1.48×10^{10}/ 2.96×10^{10}	2.96×10^{10}/ 5.92×10^{10}
06715-19	100 K	1.48×10^{10}/ 1.48×10^{10}	1.48×10^{10}/ 2.96×10^{10}	2.96×10^{10}/ 5.92×10^{10}
06715-21	Ambient	1.48×10^{10}/ 1.48×10^{10}	1.48×10^{10}/ 2.96×10^{10}	2.96×10^{10}/ 5.92×10^{10}
06715-32	100 K	1.48×10^{10}/ 1.48×10^{10}	1.48×10^{10}/ 2.96×10^{10}	2.96×10^{10}/ 5.92×10^{10}

MCT APDs proton irradiation exposure

Pre and post exposure characterisation

Parameter	Pre-exposure	Post exposure
06715-19 (exposed at 100 K)		
Cut-off wavelength @ 100 K (µm)	2.46	2.45
Cut-off wavelength @ 140 K (µm)	2.44	2.43
APD gain exponent	0.380	0.389
Quantum efficiency (%)	73.3	67.2
Excess noise factor (Max)	1.07	1.05
Read noise @unity gain (mV)	0.329	0.391
Dark Noise @ 110 K (mV)	0.225	0.222
Dark Current @110 K (electrons/pixel/second)	2372.42	3419.27
06715-32 (exposed at 100 K)		
Cut-off wavelength @ 100 K (µm)	2.46	2.44
Cut-off wavelength @ 140 K (µm)	2.44	2.45
APD gain exponent	0.370	0.351
Quantum efficiency (%)	61.0	69.4
Excess noise factor (Max)	0.97	1.03
Read noise @unity gain (mV)	0.329	0.337
Dark Noise @ 110 K (mV)	0.217	0.224
Dark Current @110 K (electrons/pixel/second)	1835.39	2909.44

Parameter	Pre-exposure	Post exposure
06715-14 (exposed at ~292 K)		
Cut-off wavelength @ 100 K (µm)	2.43	2.40
Cut-off wavelength @ 140 K (µm)	2.43	2.39
APD gain exponent	0.353	0.359
Quantum efficiency (%)	72.4	66.0
Excess noise factor (Max)	1.00	1.01
Read noise @unity gain (mV)	0.321	0.335
Dark Noise @ 110 K (mV)	0.241	0.217
Dark Current @110 K (electrons/pixel/second)	2039.33	1998.54
06715-21 (~292 K)		
Cut-off wavelength @ 100 K (µm)	2.46	2.45
Cut-off wavelength @ 140 K (µm)	2.45	2.44
APD gain exponent	0.408	0.355
Quantum efficiency (%)	61.3	65.3
Excess noise factor (Max)	1.04	1.01
Read noise @unity gain (mV)	0.347	0.329
Dark Noise @ 110 K (mV)	0.197	0.183
Dark Current @110 K (electrons/pixel/second)	1767.42	611.80

- Excluding dark current there is no change beyond the resolution of the test solution. Indicating that for most EO parameters there has been no permanent change to the MCT APDs due to the exposure of 5.92 x 10^{10} protons cm^{-1}
- Both devices exposed at 100 K showed an increase in the dark current of ~1000 electron/pixel/second (measurements from ESO expect current currents of ~ 15)
- Below 130 K the dark current is dominated by stray light in the test kit and it is difficult to conclude if there is an increase in dark current and the magnitude of any increase

CEOI EO11 - Development of 1 Mpixel L-APD arrays

Current Programme

- Collaboration between Leonardo MW and the Australian National University
- Development of 1Mpx `SAPHIRA` APD array by Leonardo suitable for imaging in low flux conditions (eg hyperspectral)
- Integration of new array with modified preamp board and in-house cryostat by ANU
- Lab testing by ANU with existing control electronics and new space system.
- Testing of entire system in ANU's 'Wombat XL' Space Simulation Facility.

A SAPHIRA array will be used in the planned 'Emu' ISS mission to detect water around stars (launch 2020/2021).

Credit Australian National University

Credit Airbus

Summary

- Leonardo currently have 3 large format ROICs which have been designed using a radiation hard cell library
- Heavy ion and proton testing has been conducted on the LFNIR ROIC to verify the performance in a radiation environment
  - Hard cell library immune to Single Event Latch-up up to LET of 67MeV/mg/cm^2
- Leonardo MW MCT APDs are resistant to ionising radiation of at least 28 krads powered and 57 krads unpowered.
- No degradation observed up to an irradiation of 2.96 x 10^{10} protons cm^{-1} for a device exposed at 100 K
- Large format MCT APD hybridized arrays will be characterized for space through collaboration with the Australian National University under the new CEOI contract

CREDITS

We would like to express our thanks to the following organisations in supporting the work presented:

CEOI

- *Heavy ion radiation testing of the LFNIR arrays (RP10G0327C23)*
- *Proton radiation testing of the LFNIR device (RP10G0435A06)*
- *Characterisation of MCT APD arrays in the ANU hyperspectral instrument (RP10G0435C201)*

The Australian National University for their contribution to the large format Saphira characterisation

ESA

- *NIR Large Format Sensor Array (ESA contract No. 4200022948/10/NL/CP)*
- *SWIR large format array (ESA contract No.4000104820/12/NL/RA)*
- *Saphira APD array proton and gamma radiation testing (ESA contract 4000118804/16/NL/BJ)*

The European Southern Observatory and the University of Hawaii for various development contracts for Saphira and large format Saphira